Orcina Project 1512

Comparison of loads from OrcaFlex and OpenFAST for the IEA 15 MW RWT

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Summary

Presented is an overview comparing select results for the International Energy Agency's (IEA) 15 MW reference wind turbine (RWT) [1] modelled in OrcaFlex and OpenFAST [4]. The study considers the structural dynamics of the turbine blade oscillating freely under gravity and the aeroelastic response of the rotor-nacelle assembly (RNA) and tower to steady, stepped, skewed and turbulent wind.

The results are generally in very good agreement, supporting both the validity of the RWT implementation in OrcaFlex and also the consistency of the two aeroelastic codes. Discrepancies are observed in tower base moment, which is attributed to differences in the data chosen to define the tower itself and the known differences in the tower structural models employed by the codes.

1. Introduction

1.1. Motivation

Originally developed as part of the IEA Wind Task 37, the IEA 15 MW RWT [1] is extensively used in the design and study of floating offshore wind turbine (FOWT) systems.

Orcina publish an example OrcaFlex implementation of this RWT, mounted upon the University of Maine VolturnUS-S reference semi-submersible platform (UMaineSemi) [3]. Since the OrcaFlex example was first published, the RWT continues to be reviewed and updated. At the time of writing, v1.1.3 is the latest revision of the RWT publicly available [2]. OrcaFlex's capability has also continued to evolve and important new functionality has been introduced including the ability to specify the blade profile's shear centre and models used to account for unsteady aerodynamics.

Concurrent to the publication of this document, the OrcaFlex example has been updated to incorporate the latest changes to the RWT and to specify the new data required to satisfy the extended OrcaFlex functionality. The purpose of this document is to summarise a validation of the updated OrcaFlex RWT model. This is done through comparison against OpenFAST simulations, covering cases that exercise the new OrcaFlex capability.

1.2. References

No.	Title
1.	Gaertner E et al, 2020, Definition of the IEA wind 15-megawatt offshore reference wind turbine Tech. Rep. NREL/TP-5000-75698, NREL, https://www.nrel.gov/docs/fy20osti/75698.pdf
2.	IEA Task 37 IEA GitHub repository, https://github.com/IEAWindTask37/IEA-15-240-RWT
3.	K03 15MW semi-sub FOWT, Orcina, https://www.orcina.com/wp-content/uploads/examples
4.	OpenFAST, v3.1.0, NREL, https://github.com/OpenFAST/openfast/releases/tag/v3.1.0
5.	ROSCO v2.6, NREL, https://github.com/NREL/ROSCO/releases/tag/v2.6.0
6.	BeamDyn inputs from sectional beam properties, E. Branlard, J. Jonkman, 5/3/20, NREL, https://openfast.readthedocs.io/en/main/_downloads/fd7a8bc10f2371a50828391f75170032/beamdyn_inputs_sectional_props.pdf
7.	TurbSim, NREL, https://www.nrel.gov/wind/nwtc/turbsim.html

Table 1 – List of References

1.3. Abbreviations

Abbreviation	Description
DOFs	Degrees of freedom
DTU	Technical University of Denmark
ETM	Extreme turbulence model
FOWT	Floating offshore wind turbine
IEA	International Energy Agency
IEC	International Electrotechnical Commission
NREL	National Renewable Energy Laboratory
ROSCO	Reference Open Source Controller
RNA	Rotor-nacelle assembly
RWT	Reference wind turbine
UA	Unsteady aerodynamics
UMaineSemi	University of Maine VolturnUS-S reference semi-submersible platform

Table 2 – List of Abbreviations

2. Modelling

2.1. OpenFAST

OpenFAST is an open-source wind turbine simulation tool developed by the National Renewable Energy Laboratory (NREL) [4]. The IEA 15MW RWT v1.1.3 release [2] includes a full OpenFAST dataset, with multiple foundation types. For the purpose of this study, we consider the RNA and tower associated with the UMaineSemi foundation variant, but truncated at the tower base. This is done to remove the complexity of the floater model and to allow us to focus on the turbine's aeroelastic response.

OpenFAST supports two structural solvers to calculate blade dynamics: ElastoDyn and BeamDyn. In this study, all simulations have been conducted using BeamDyn because it is a higher fidelity model and more appropriate to modelling blades undergoing large, 6DOF deflections.

The OpenFAST model has been kept as close as possible to that available through the v1.1.3 RWT release, with the following changes:

1. The platform's degrees of freedom (DOFs) were excluded
2. CompElast was set to 2 (i.e. BeamDyn) and the timestep was reduced to 0.0005s
3. The AeroDyn tower description has been edited to be consistent with the tower associated with the VolturnUS-S semi-submersible foundation variant
4. The AeroDyn UAMod was changed to "2", (i.e. the Gonzalez's variant), which was found to reduce undesirable large blade oscillation at higher wind speeds
5. Tower Cd was increased to 1

In this study, all OpenFAST simulations have been run using v3.1.0.

2.2. OrcaFlex

The OrcaFlex RNA model has been generated from the v1.1.3 RWT OpenFAST dataset. To do this, the blade structural properties, as required by OrcaFlex, have been calculated from the associated BeamDyn 6X6 matrices following the conventions documented in [6]. The blade mass per unit length was then scaled up by 2.06% to match the total mass documented for the v1.1.3 RWT in *IEA-15-240-RWT_tabular.xlsx* [2].

The tower data was derived directly from the v1.1.3 RWT ontology. This yields a slightly different outer diameter, stiffness and mass profile than would be derived from the associated ElastoDyn tower data. The tower damping coefficients were matched with the HAWC2 dataset coefficients, because they parametrise a damping model that is consistent with that employed by OrcaFlex turbine blades, i.e. Rayleigh damping.

In this study, all OrcaFlex simulations have been run using v11.3.

2.3. Controller

For both the OrcaFlex and OpenFAST simulations, the controller used was NREL's Reference Open Source Controller (ROSCO) v.2.6.0 [5]. The controller input file was that associated with the UMaineSemi, and distributed as part of the v1.1.3 RWT release, but with the floating specific feedback disabled (i.e. Fl_Mode = 0). This mode was inappropriate for the tower only configuration.

2.4. Comparison of data

Also distributed as part of the v1.1.3 RWT release is a HAWC2 dataset. HAWC2 is an aeroelastic code developed and distributed by DTU Wind Energy. The relevant HAWC2 blade structural data, contained in *IEA_15MW_RWT_Blade_st_noFPM.st* [2], is in a format much closer to that required by OrcaFlex. It has been determined independently of the BeamDyn dataset, but from the same underlying RWT ontology.

To confirm the blade structural properties have been correctly calculated from the BeamDyn 6X6 mass and stiffness matrices, the OrcaFlex blade profile has been compared against the HAWC2 dataset in **Figure 1** and **Figure 2**. That comparison is presented using the OrcaFlex blade profile frame conventions, but offsets are given in meters relative to the half cord position.
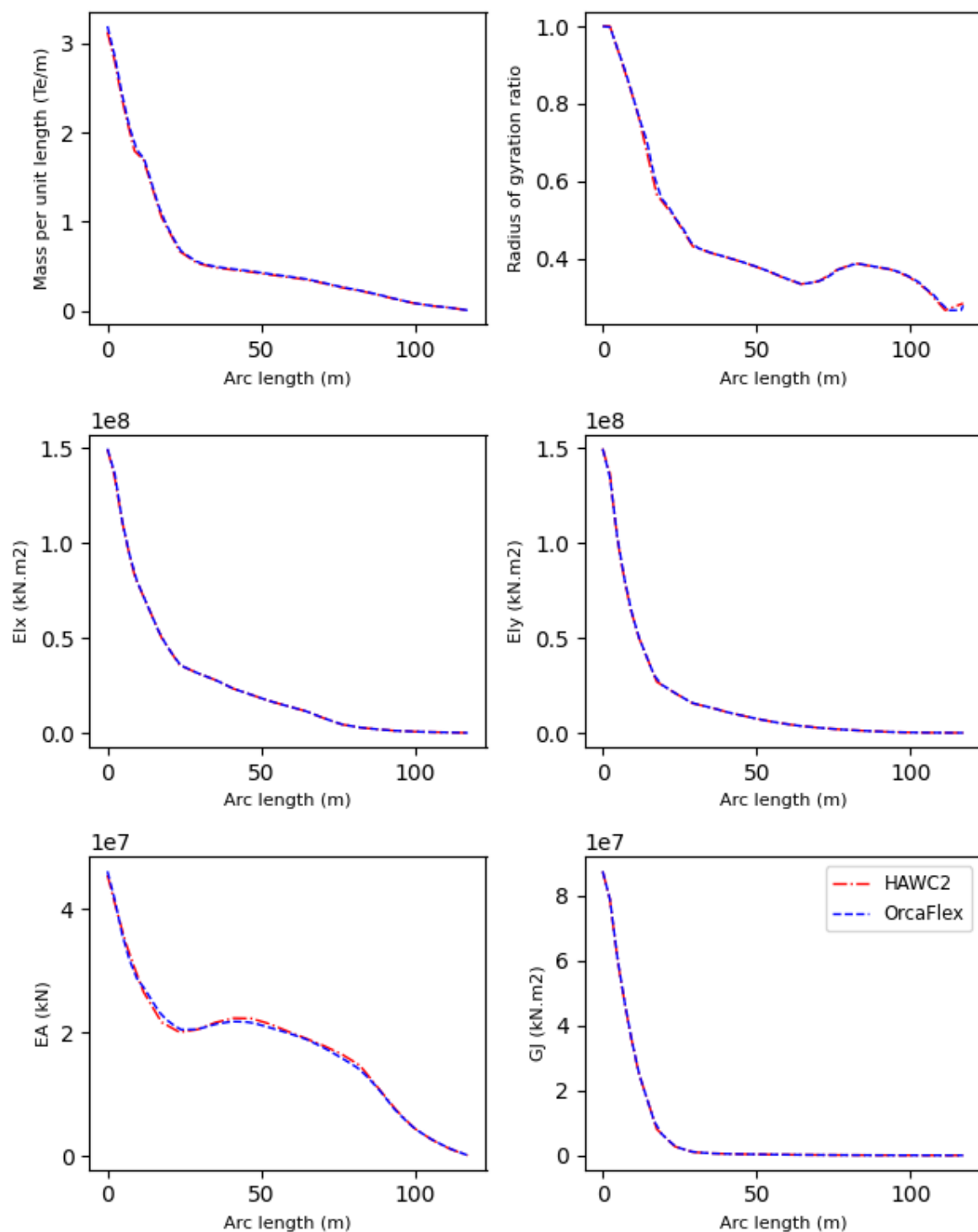
Figure 1 - Comparison of blade structural properties.
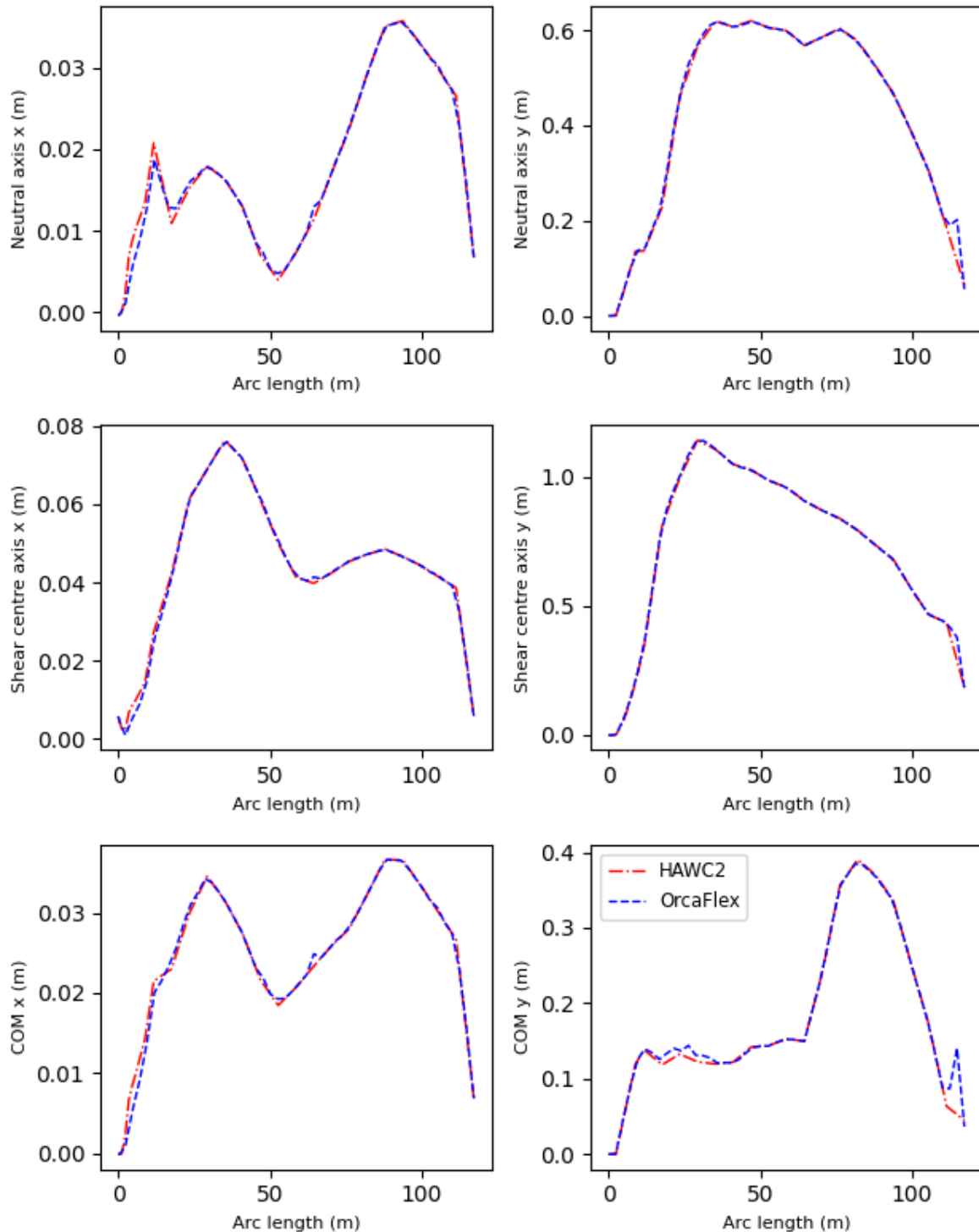
Figure 2 - Comparison of blade structural origins.

In general the comparison of the OrcaFlex and HAWC2 data is very strong, which suggest the methodology by which the OrcaFlex data has been generated is sound. There are a few small discrepancies, especially near the tip, which are attributed to the resolution of the datasets, the associated interpolation required, and possibly differences in the methodologies used to calculate the HAWC2 and BeamDyn data sets.

3. Results

3.1. Dynamic blade cantilever

To assess the consistency of the OrcaFlex and BeamDyn blade models, a series of dynamic cantilever test were conducted. A single blade was fixed at the root, with its axis perpendicular to the vertical, excluded from the statics solve and then dynamically allowed to fall and oscillate freely under gravity.

For this cantilever test, aerodynamic loading was included, but the aerodynamic blade element momentum, unsteady aerodynamics, and tower interaction calculations were all excluded. As were the control system and tower structural model.

To make sure both flapwise and edgewise bending was excited, the test was conducted for three pitch angles: 0, 45, and 90 degrees. Blade tip deflections and root loads are compared for the first 30s in **Figure 3** through to **Figure 11**.

Across all simulations the agreement was excellent. There is a very slight drift in the results as time progresses, possibly caused by small difference in the interpolation, and integration, of the discrete inertial properties, or differences in the time integration schemes used.
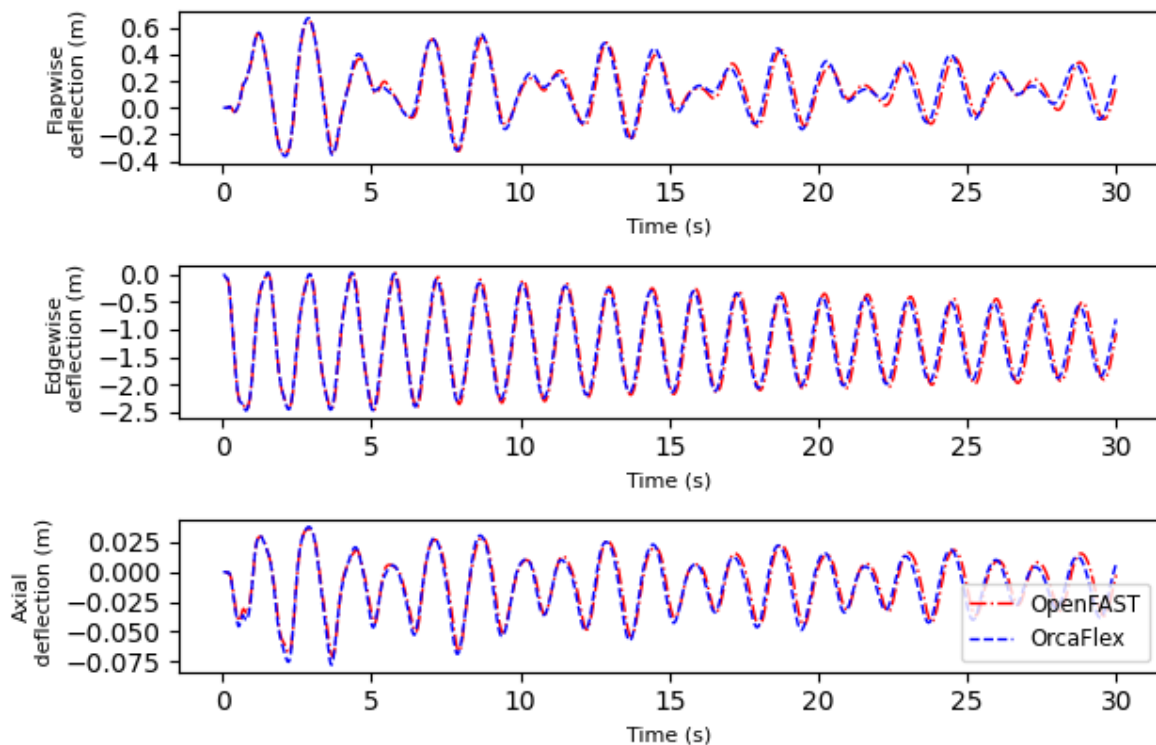
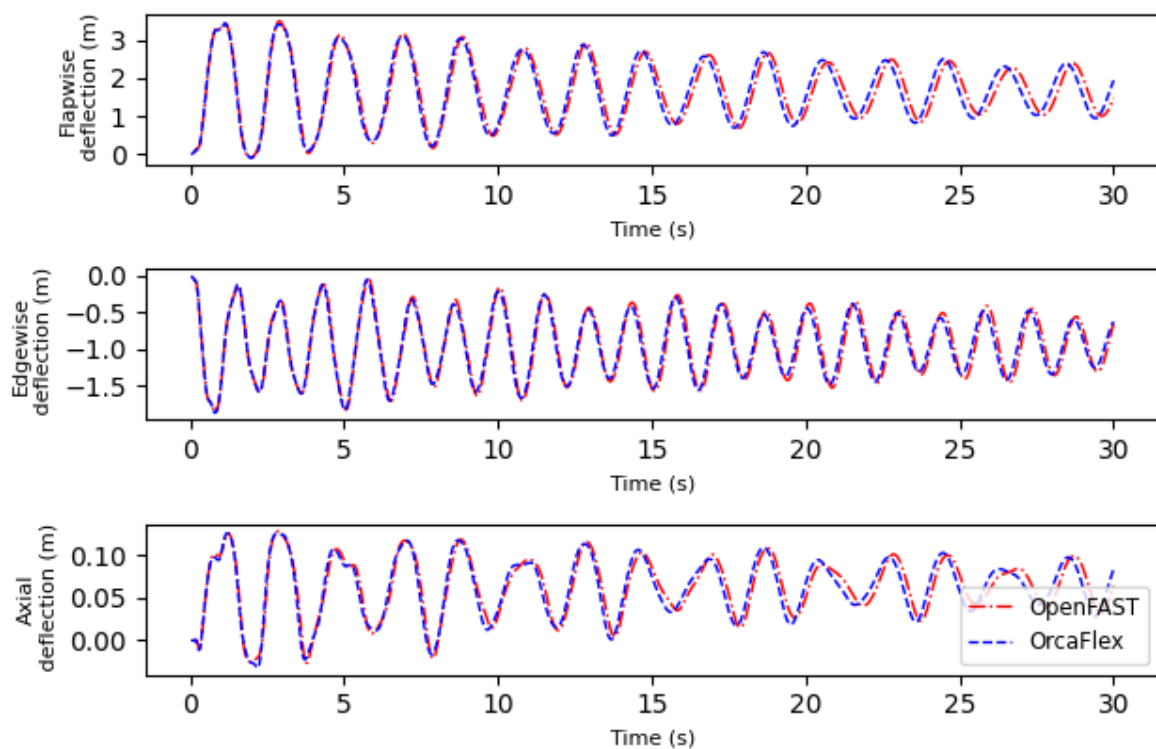**Figure 3 – Comparison of tip deflection for dynamic cantilever test, 0 degree blade pitch.**

Figure 4 – Comparison of tip deflection for dynamic cantilever test, 45 degree blade pitch.
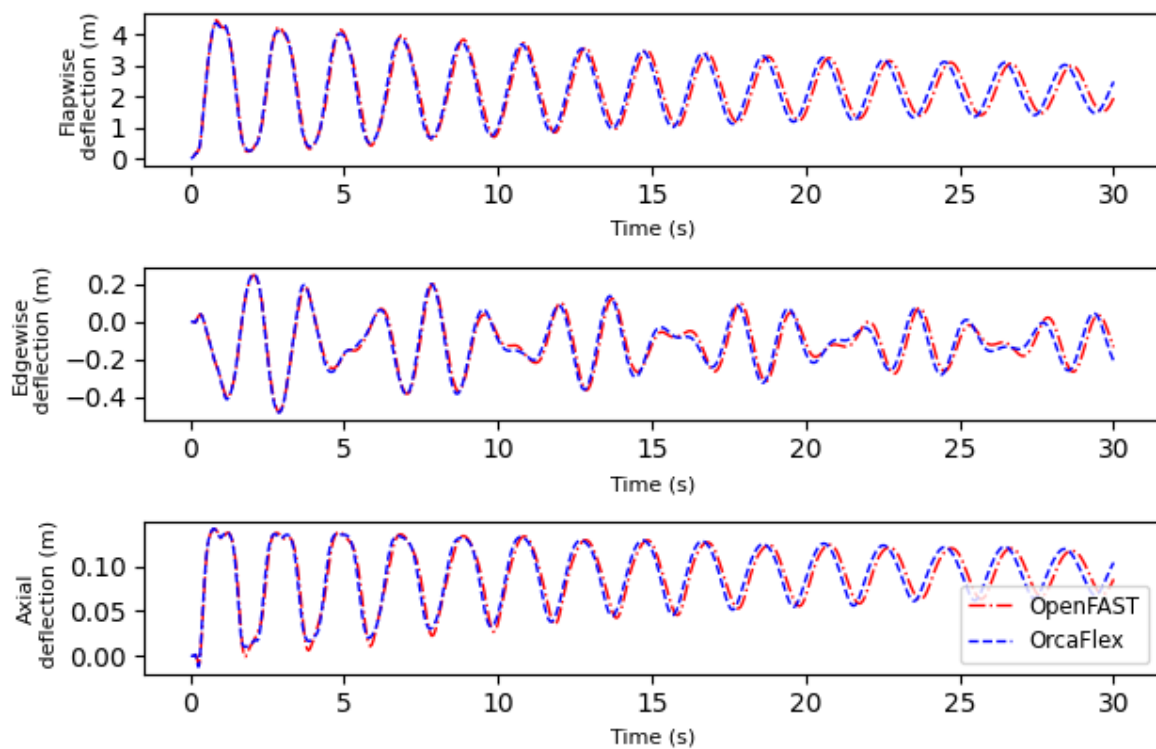

Figure 5 - Comparison of tip deflection for dynamic cantilever test, 90 degree blade pitch.
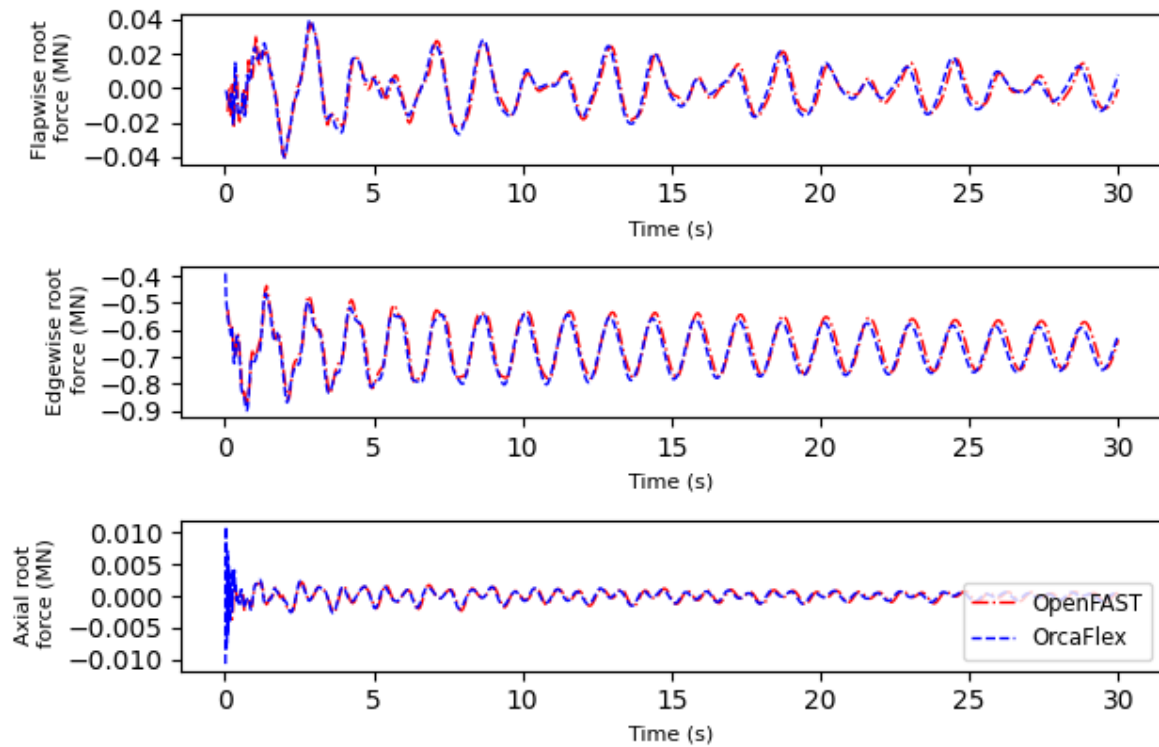
Figure 6 – Comparison of root force for dynamic cantilever test, 0 degree blade pitch.
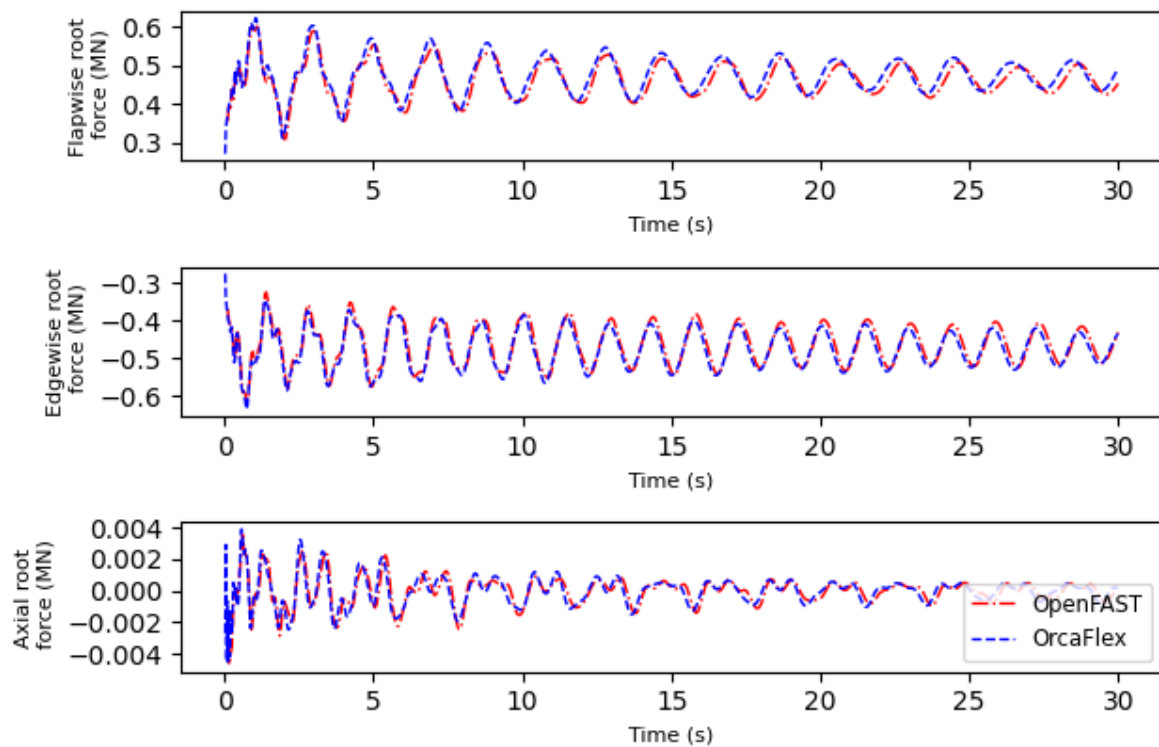

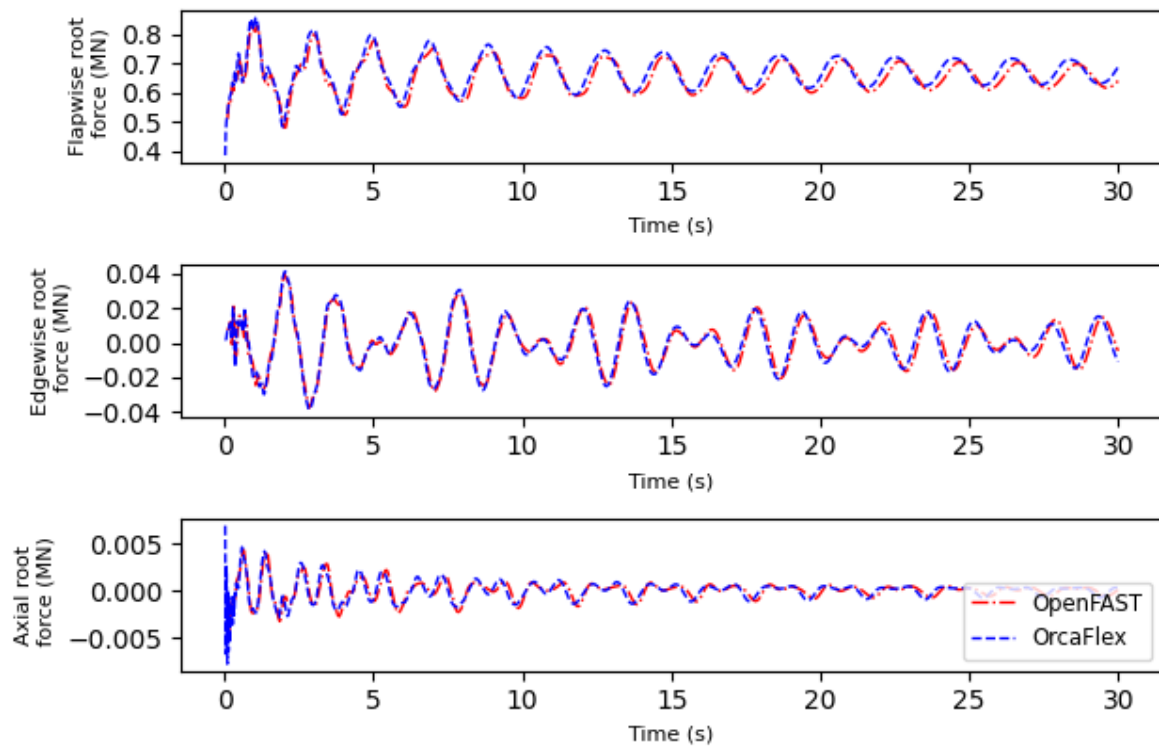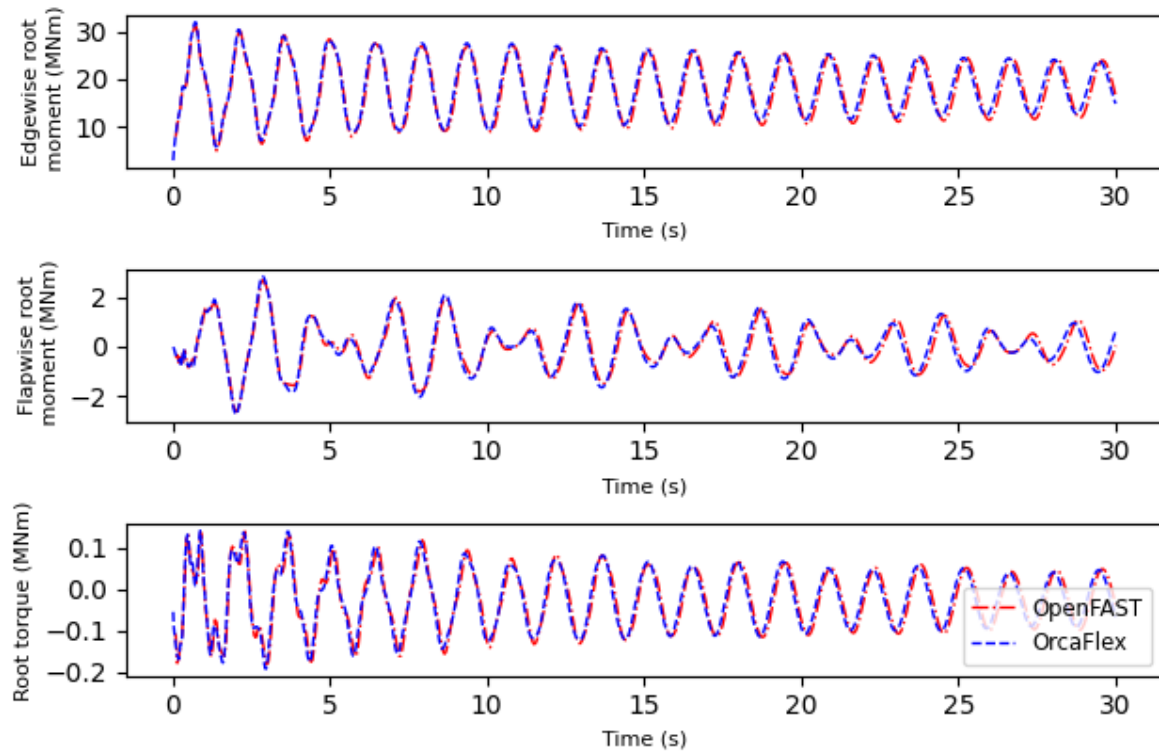**Figure 7 – Comparison of root force for dynamic cantilever test, 45 degree blade pitch.**

Figure 8 - Comparison of root force for dynamic cantilever test, 90 degree blade pitch.

Figure 9 – Comparison of root moment for dynamic cantilever test, 0 degree blade pitch.
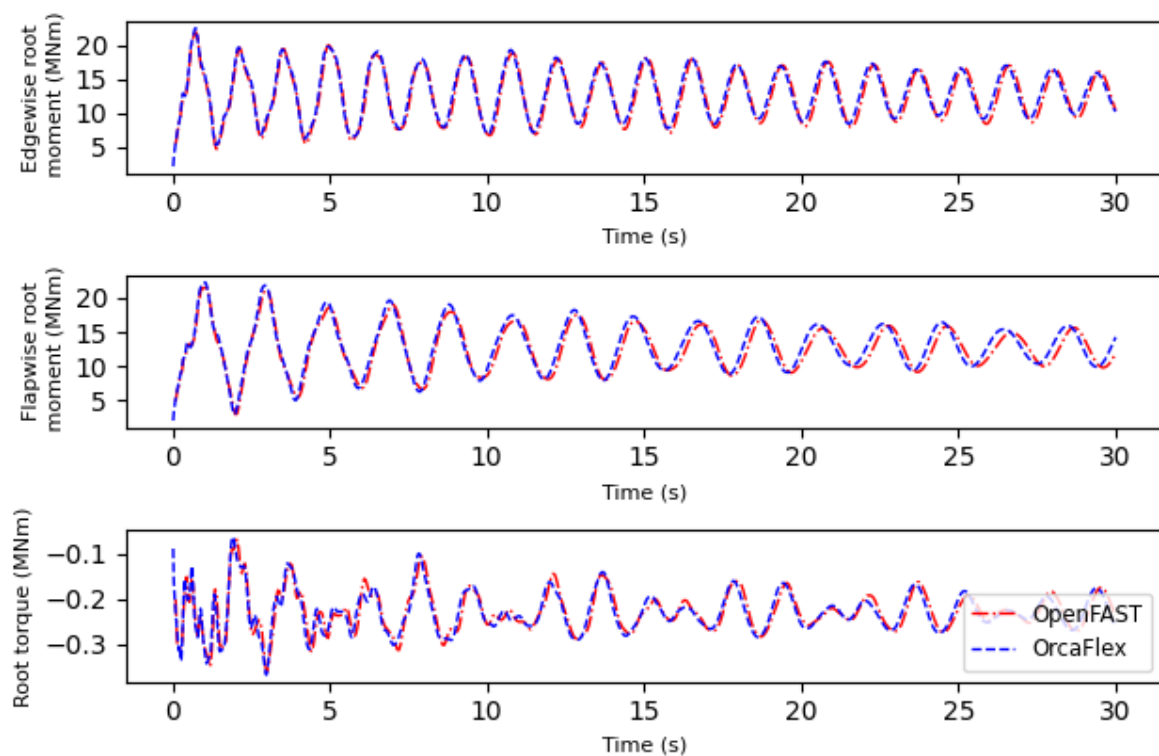
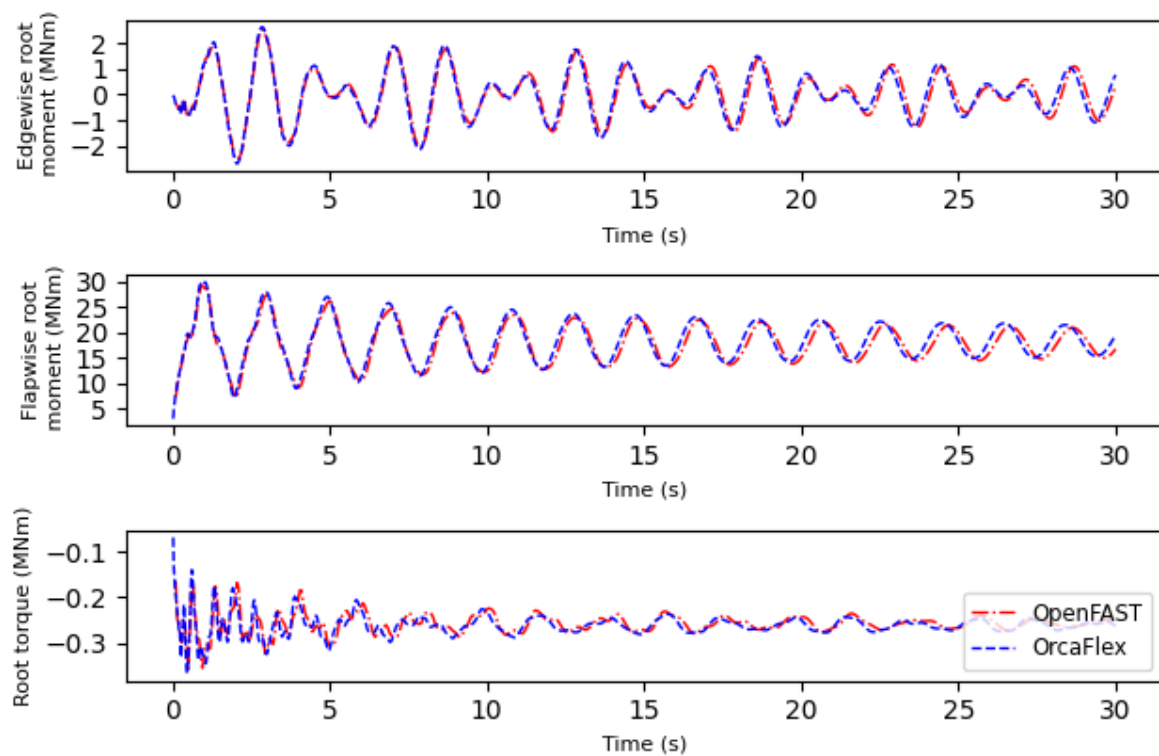**Figure 10 – Comparison of root moment for dynamic cantilever test, 45 degree blade pitch.**

Figure 11 – Comparison of root moment for dynamic cantilever test, 90 degree blade pitch.

3.2. Steady-state response

The steady-state response for the full RNA and tower was then compared between OrcaFlex and OpenFAST. To determine this, the turbine was subjected to a constant wind speed, without shear, and the simulation was run long enough to remove any significant initial transient behaviour. The results are then averaged over the final 100s of the simulation. Wind speed between 3 m/s to 25 m/s, at 1 m/s, increments were considered. The results are shown in **Figure 12** and **Figure 13**.
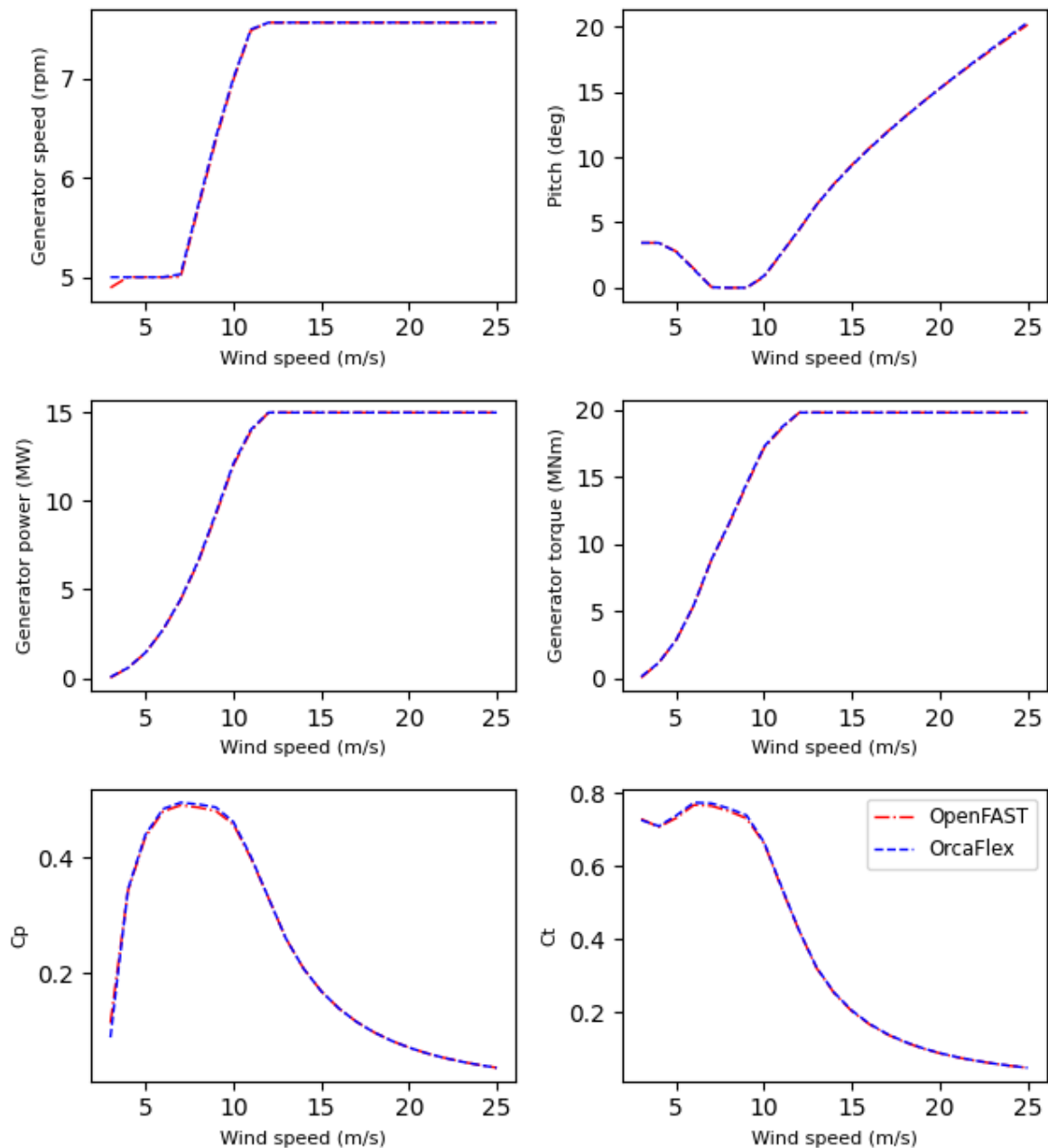

Figure 12 - Comparison of the aerodynamic and operational steady-state response.
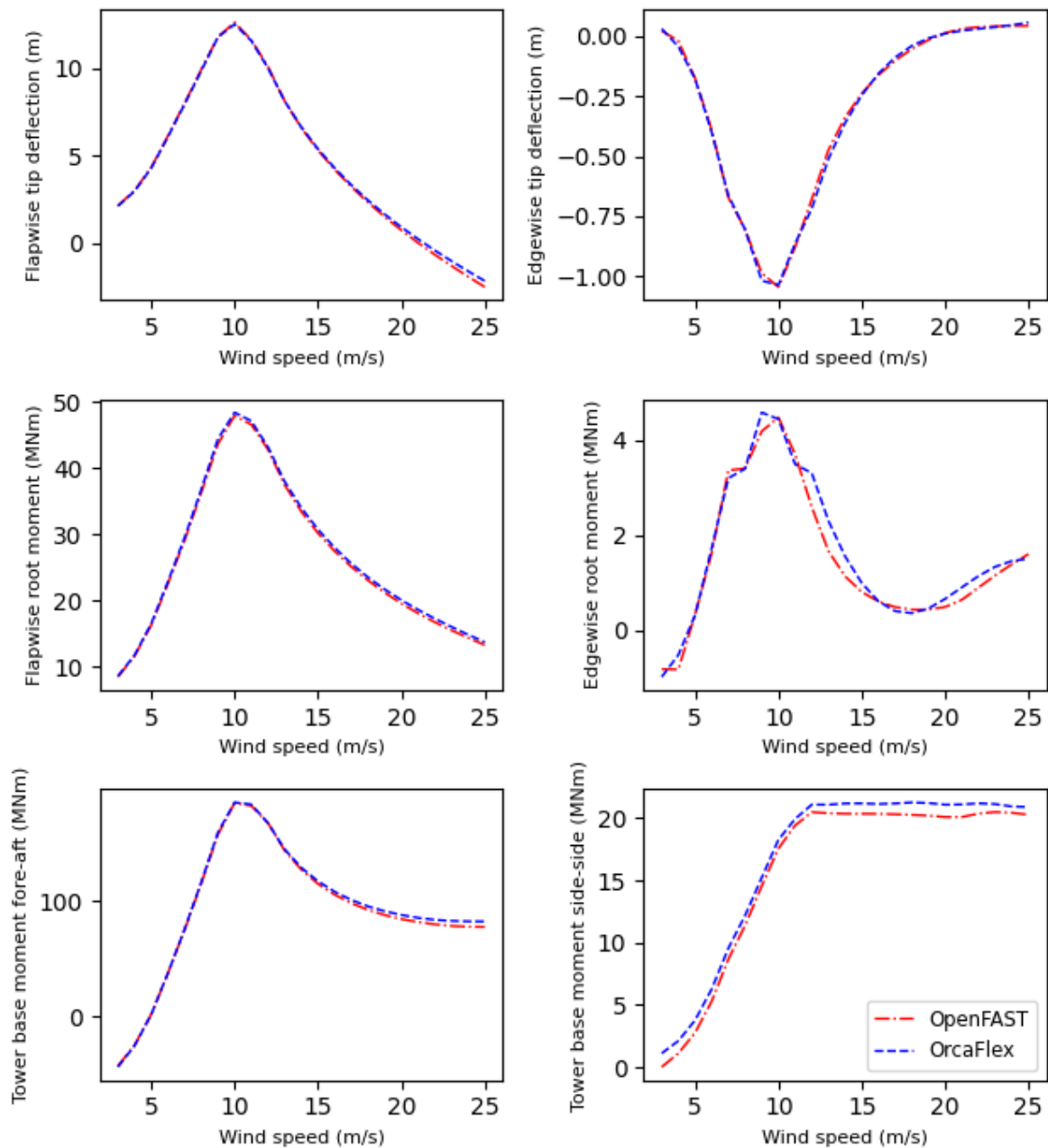
Figure 13 - Comparison of the blade and tower steady-state response.

The comparison is good. In several results, small differences are present at low wind speeds, attributed to initial transients taking longer to settle.

Edgewise root moment displays some disparities. However, this result, in particular, is very sensitive to the period over which the average is calculated. Studying this sensitivity suggests that the results would converge further if the simulation duration, and the period over which the average is taken, were to be increased further.

Across all wind speeds, there is a systematic difference in tower base side-to-side moment. As discussed in Section 3.5 this can be attributed to differences in the tower data and the structural models used to calculate the tower's response.

3.3. Step-wind response

The dynamic response of the RNA and tower, to stepped wind time history, was compared between OrcaFlex and OpenFAST. The turbine was subjected to a constant wind speed of 3 m/s for the first 100s, included to help remove the influence of initial transients, and then the wind speed was incremented, by 1 m/s every 40s, up to 25 m/s. A time history of the wind speed is shown in **Figure 14**.

The simulation was repeated twice: with and without a wind skew angle of 35 degrees. The results are shown in **Figure 15** through to **Figure 18**.

Again, the comparison is very good with the only significant difference observable in the tower base moment. As discussed in Section 3.5 this can be attributed to differences in the tower data and the structural models used to calculate the tower's response.
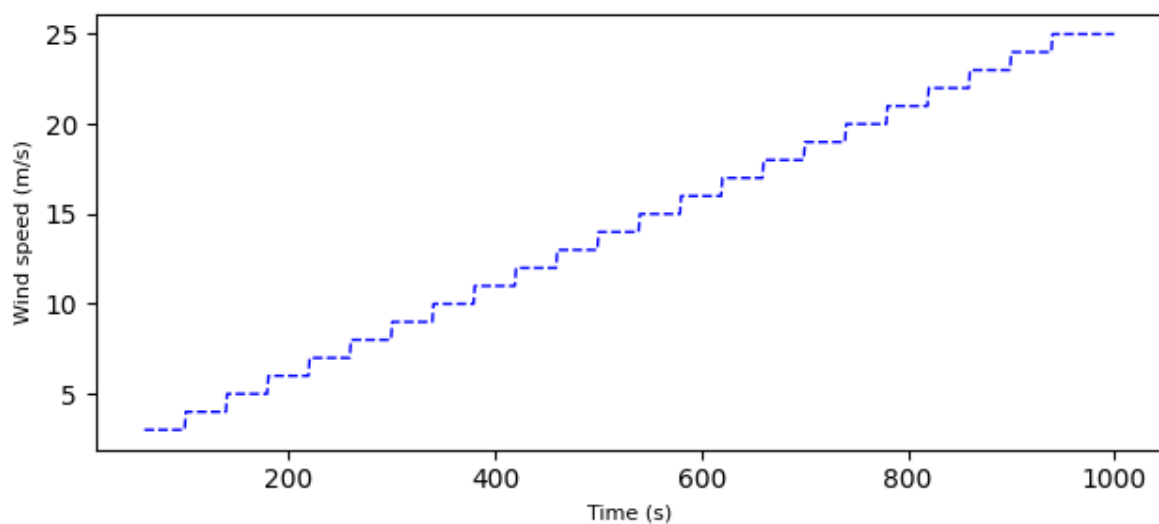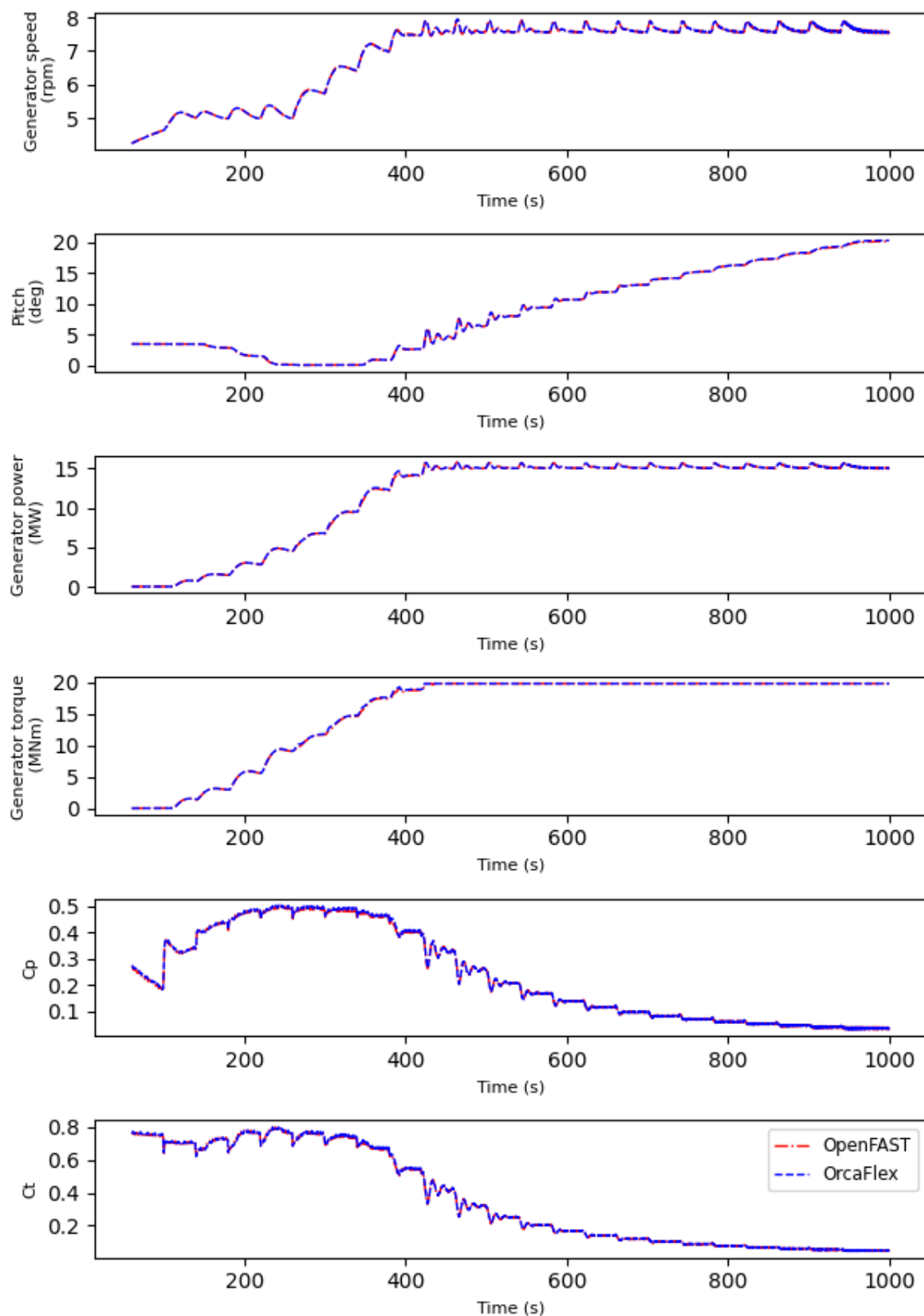

Figure 14 - Stepped wind time history.

Figure 15 - Comparison of aerodynamic response to stepped wind, without skew.
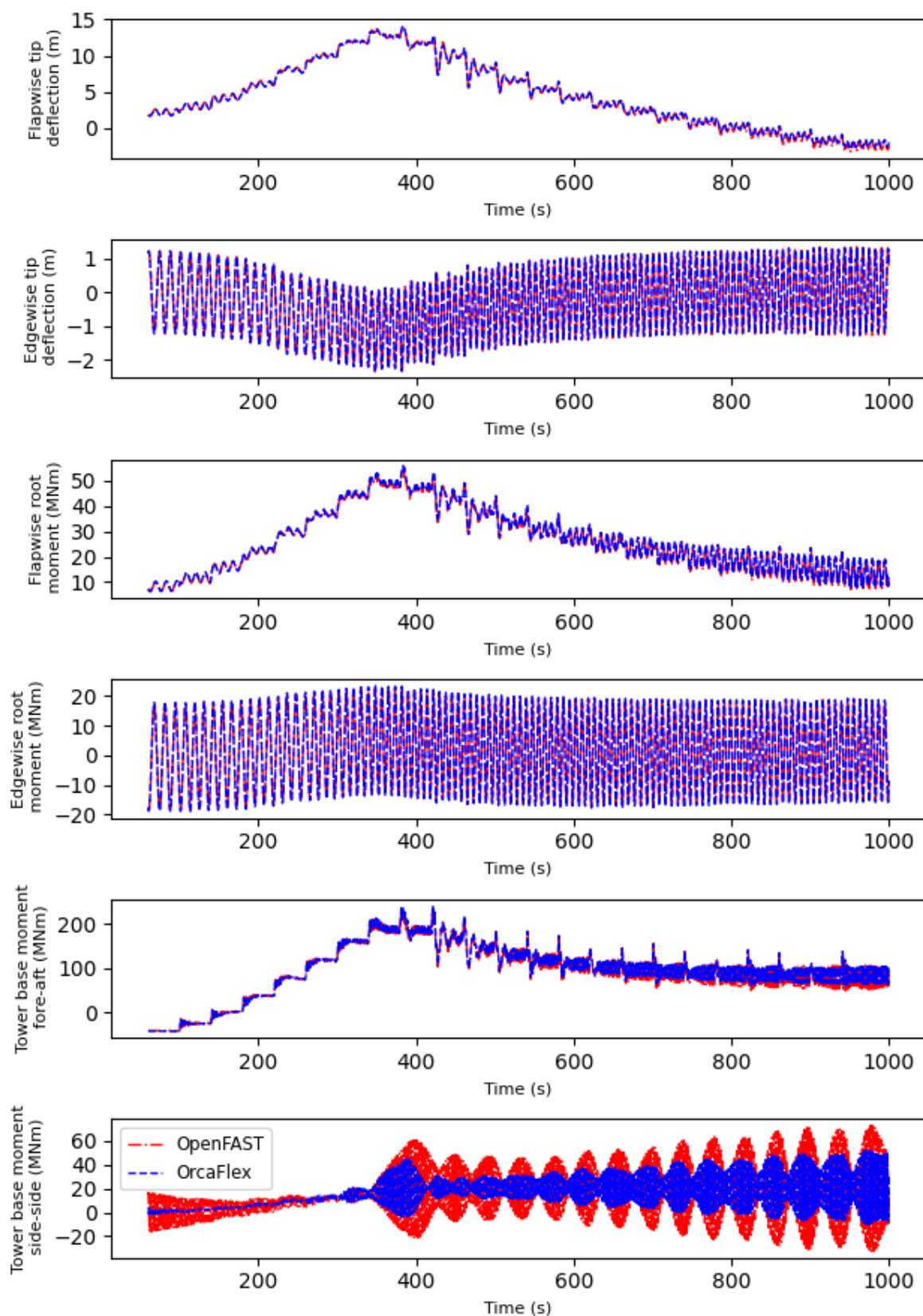
Figure 16 - Comparison of blade and tower response to stepped wind, without skew.
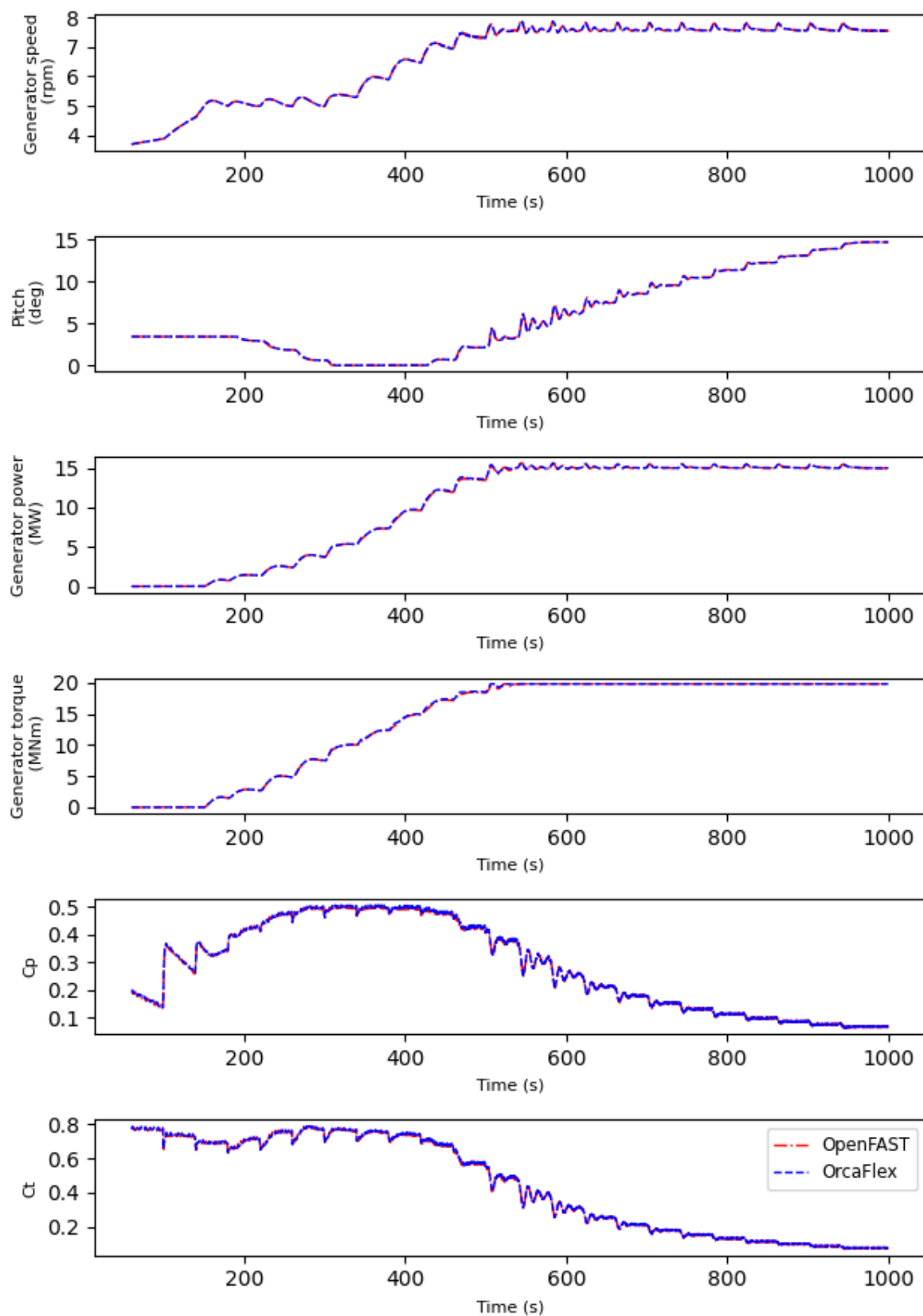
Figure 17 - Comparison of aerodynamic response to a stepped wind, with skew.
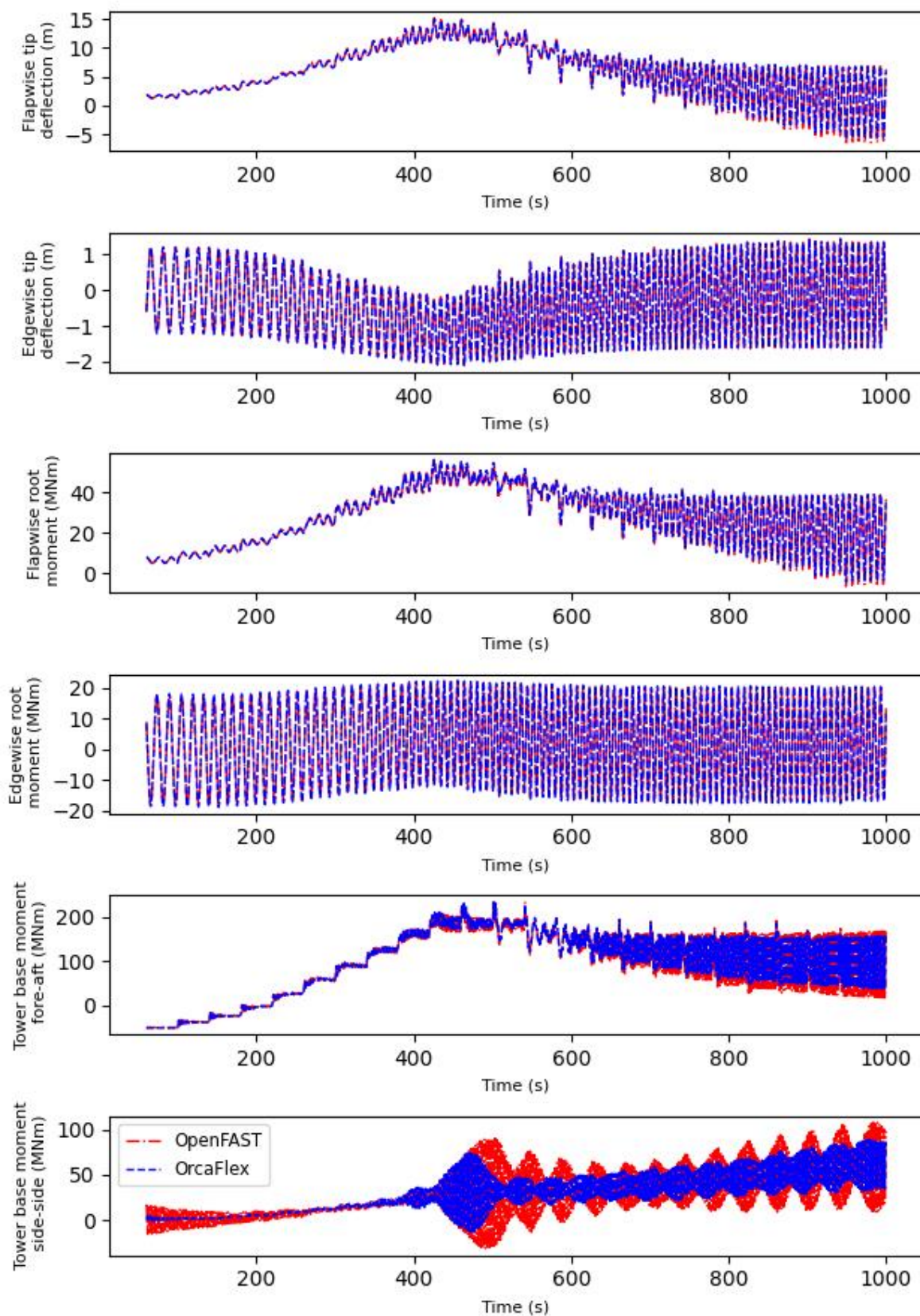
Figure 18 - Comparison of blade and tower response to a stepped wind, with skew.

3.4. Turbulent wind

Finally, the dynamic response of the RNA and tower, to turbulent wind, was compared between OrcaFlex and OpenFAST. A full-field, IEC 61400-1IB ETM turbulent wind, with 15 m/s mean speed was generated using TurbSim [7]. The response was simulated for 300s, of which the final 50s are compared in **Figure 19** and **Figure 20**. Results are consistent with previous sections.
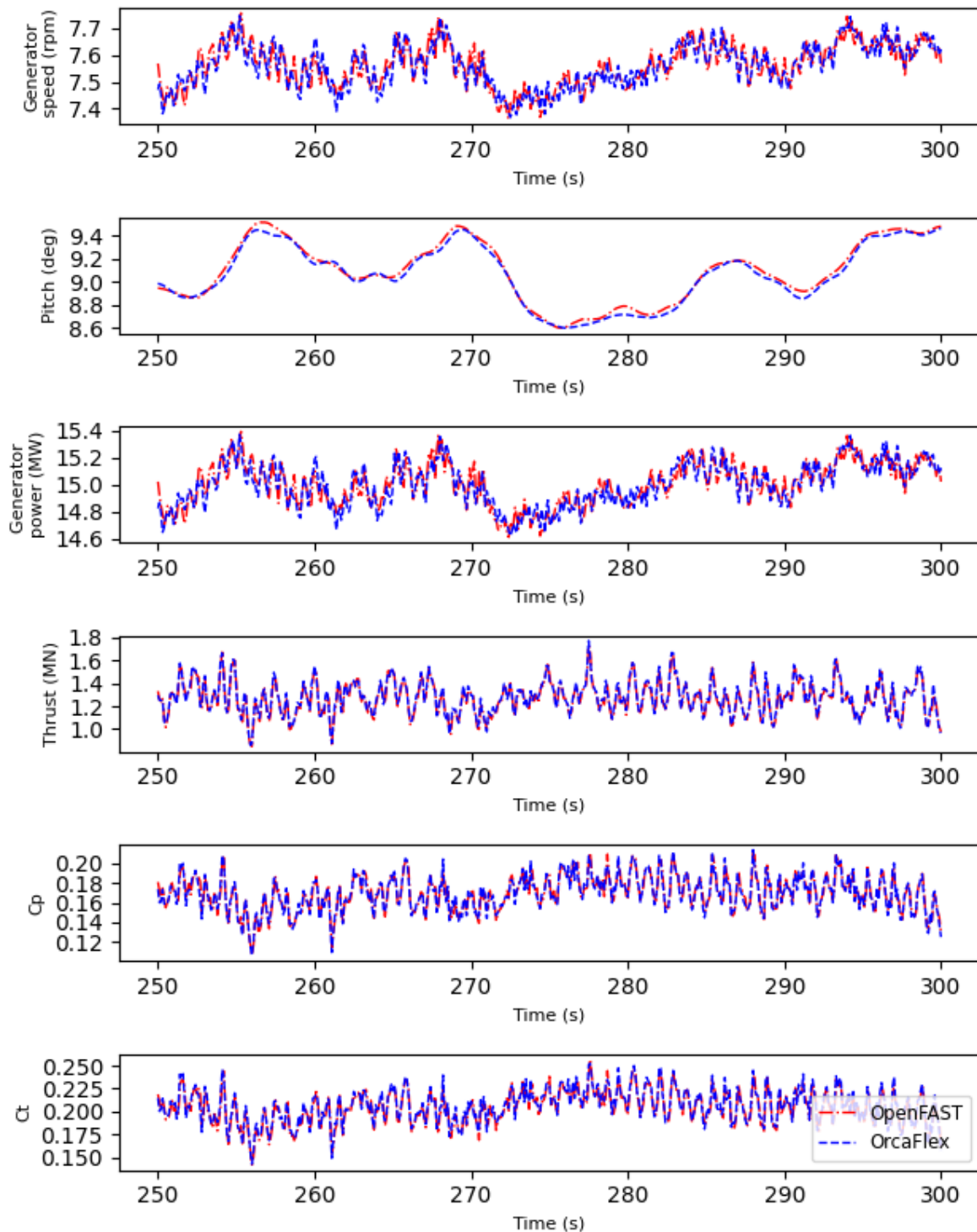

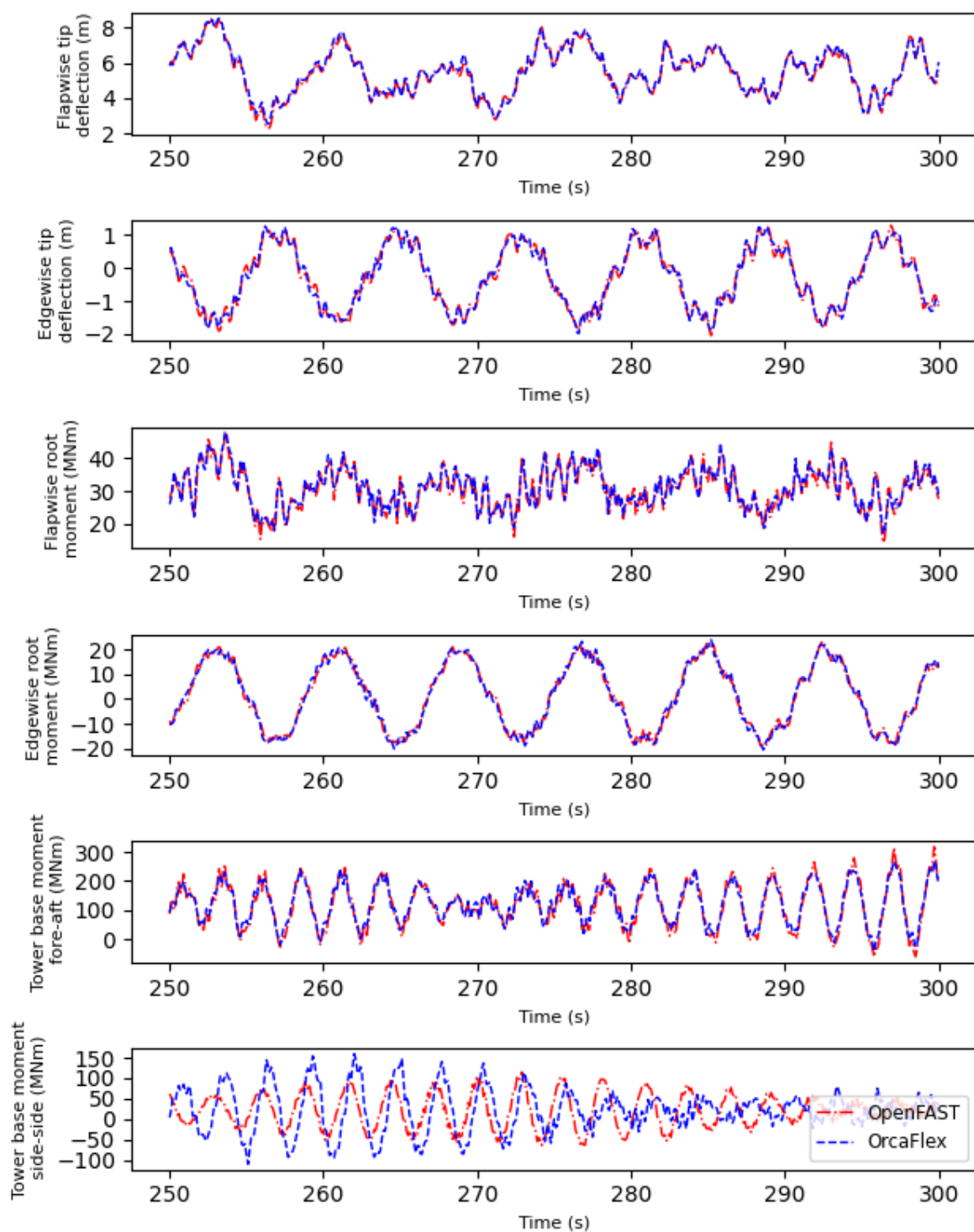**Figure 19 – Comparison of aerodynamic and operational response to turbulent wind.**

Figure 20 – Comparison of blade and tower response to turbulent wind.

3.5. Turbulent wind with modified tower

Throughout the study, differences have been noted in the tower base moment. As described in Section 2, the OrcaFlex tower data has been derived directly from the RWT ontology, rather than the associated ElastoDyn data, and the differences in data will make a small contribution.

More significantly, unlike OrcaFlex, the ElastoDyn tower model doesn't capture the tower's torsional response and solves for only the first two tower bending modes. This fundamental difference in the two structural solvers means that damping is also defined differently: stiffness proportional Rayleigh damping in OrcaFlex, and percentage critical per mode in OpenFAST. This is why the tower damping values were adopted from the HAWC2 data set, which is in the same format required by OrcaFlex.

It is not possible to achieve the same OpenFAST modal damping levels in OrcaFlex, for both modes. However, to help confirm that the discrepancies may be attributed to differences in the tower models, the OrcaFlex tower model was modified to (i) tune the tower damping to match the OpenFAST damping, in the first tower mode, and (ii) suppress he tower's torsional DOF by using an artificially high torsional stiffness. The turbulent wind study presented in section 3.4 was then repeated with this modified tower.

The comparison with OpenFAST is shown in **Figure 21** and **Figure 22**. The tower side-to-side base moment now compares well and, in addition, the comparison for other results (e.g. generator power and blade pitch) are also improved. This suggests that the tower model is the primary contribution to the observed discrepancies.
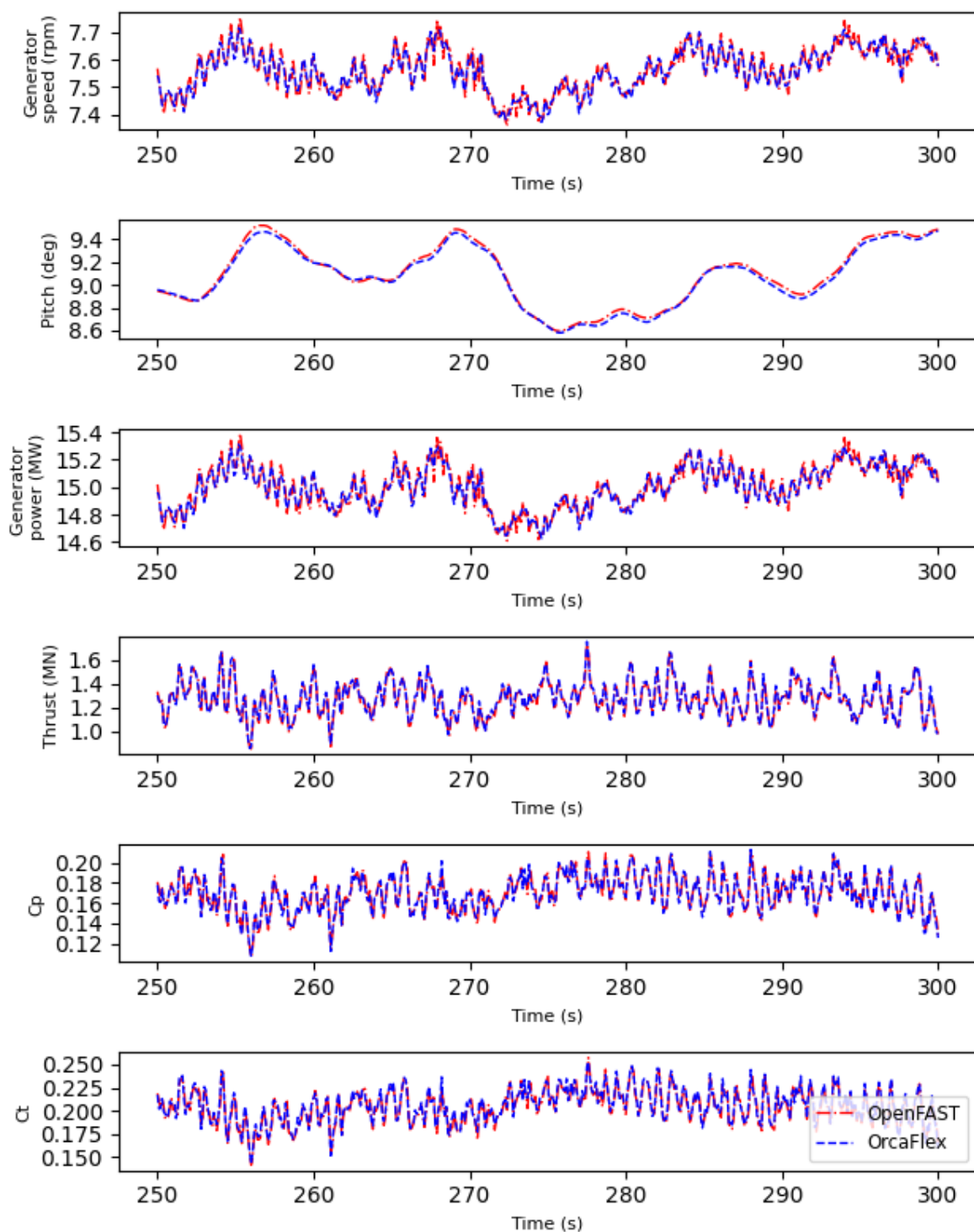
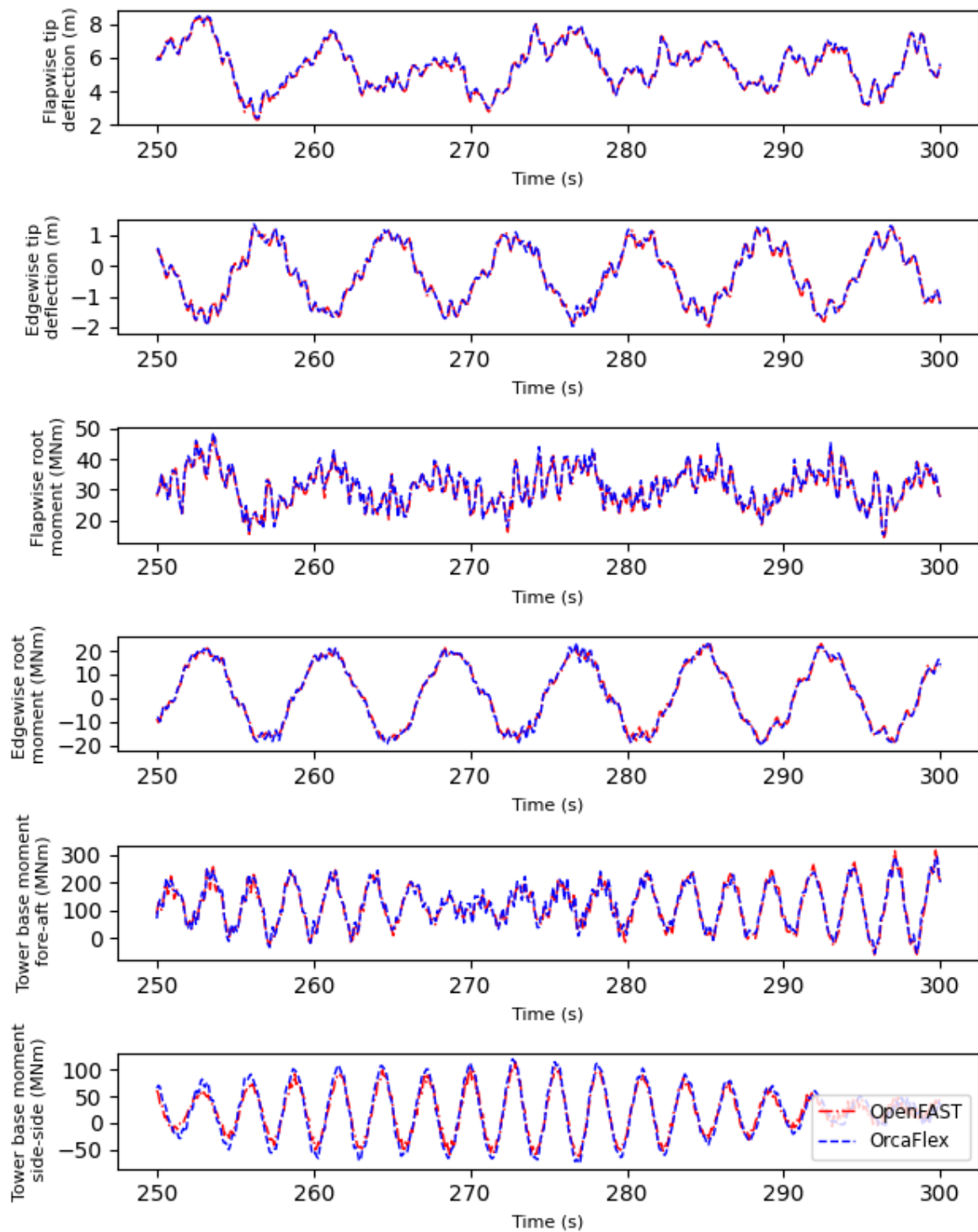**Figure 21– Comparison of aerodynamic and operational response to turbulent wind, with modified tower.**

Figure 22 - Comparison of blade and tower response to turbulent wind, with modified tower.

4. Conclusions

Presented in this report is an aeroelastic comparison of the IEA 15 MW RWT RNA and tower, as implemented in OpenFAST and a new up-to-date OrcaFlex example implementation.

With a few exceptions, the OrcaFlex implementation of the RWT RNA has been kept as close as possible to the OpenFAST dataset, as distributed as part of the v1.1.3 IEA 15 MW RWT release. The tower model was implemented using the associated wind turbine ontology as the primary reference, resulting in slightly different structural properties when compared to the OpenFAST data set.

For OpenFAST blade dynamics, the higher fidelity BeamDyn structural model was chosen, over ElastoDyn, for all OpenFAST simulations.

The structural response of the blade, in a cantilever configuration, freely oscillating under gravity was first compared. The very strong agreement between loads and displacements predicted by OrcaFlex and OpenFAST suggests the BeamDyn data has been correctly interpreted and incorporated into the OrcaFlex model.

Next the response of the RNA and tower to steady, stepped, skewed, and turbulent wind were compared. Again, the agreement was generally very good, supporting both the validity of the RWT RNA and tower implementation in OrcaFlex, and also the consistency of the two aeroelastic code's functionality.

Only in the tower base side-to-side moment were significant differences observed. As discussed in Section 3.5 this can be attributed to differences in the tower data and the structural models used to calculate the tower's response.